F49620-00-C-0018

NONLINEAR AEROELASTICITY FOR HYPERSONIC FLIGHT VEHICLES

Informal Technical Report
April 15 to November 30, 2000

November 27, 2000

CRAD-0006-TR-7411

TO: USAF
AIR FORCE OFFICE OF SCEINTIFIC RESEARCH
ARLINGTON, VIRGINIA

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SUBJECT: Contract F49620-00-C-0018, "Non-Linear Aeroelasticity for Hypersonic Flight Vehicles (Basic), Informal Technical Report

TO: USAF / AFMC
Defense Technical Information Center/OCA
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Fort Belvoir, VA 22060-6218

ATTACHMENT: (1) Informal Technical Report
CRAD-0006-TR-7411, for the period of
15 April 2000 through 30 November 2000

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High Speed Aerodynamics Group — Loads and Dynamics Group

Nonlinear Aeroelasticity for Hypersonic Flight Vehicles

Informal Technical Report
April 15 - November 30, 2000

Contract No. F49620-00-C-0018

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Objective

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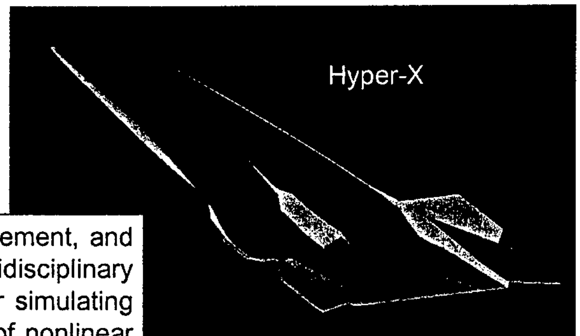

Formulate, implement, and validate a multidisciplinary analysis tool for simulating the interaction of nonlinear aerodynamics, nonlinear structures, and flight controls for hypersonic flight vehicles

Hypersonic vehicles, like the Hyper-X, have unique aerodynamics/structures/controls/propulsion interactions. Their aerodynamics is dominated by the fuselage and their wings are all-moving control surfaces. These missile-like configurations also feature highly integrated airbreathing propulsion systems with thin cowls. The shell structures of these cowls have tight geometric requirements for the inlet and the finely tuned shock systems to work. On the other hand, these cowls are subject to aerothermoelastic distortions which can significantly degrade the efficiency of the propulsion system. Hypersonic vehicles are also characterized by (relatively) cold and hot structures. To prevent overheating and to control thermal stress, accurate estimates of the temperature distribution throughout the vehicle are required.

Currently, the analysis of hypersonic vehicles rely primarily on methods that use linear structures and linear aerodynamics. Today, advances in computational fluid dynamics (CFD) and computer technology permit a limited number of nonlinear aerodynamic analyses. Thus far, this approach has not succeeded in reaching the goal of producing a viable hypersonic vehicle.

As a first step towards this goal, the objective of this project is to develop a multidisciplinary analysis tool for modeling the interaction of nonlinear aerodynamic, nonlinear structures, and flight controls for hypersonic vehicles.

Summary of Progress

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- Completed framework for a nonlinear static-aeroelastic analysis system
- Integrated all five modules
  - CFL3D : Performs aero (Euler/Navier-Stokes) analysis
  - COMETRAN : Maps aero loads to structural nodes
  - NASTRAN : Performs structural analysis
  - Spline3D : Maps structural deformation to aero grid
  - CSCMDO : Perturbs aero volume grid
- Completed testing

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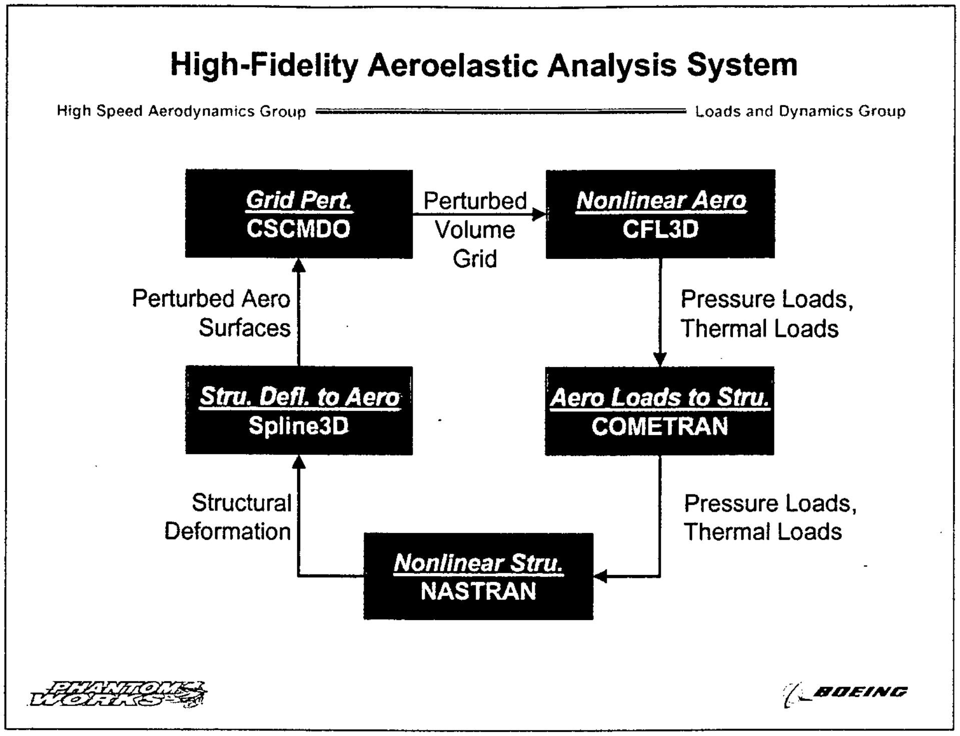
A framework for aeroelastic analysis of air vehicles, using nonlinear aerodynamics and nonlinear structural analyses, has been completed. All five modules have been integrated into the system. The primary modules are CFL3D and NASTRAN. CFL3D performs nonlinear aerodynamic (Euler/Navier-Stokes) analysis, while NASTRAN performs the nonlinear structural analysis. COMETRAN is used for mapping aerodynamic loads (pressure and thermal) from the CFD (Computational Fluid Dynamics) grid to the nodes of the structural FEM (Finite Element Model). Typically, the CFD grid is finer than the FEM. Spline3D is used to map the structural deformation onto the CFD surface grid. CSCMDO perturbs the CFD volume grid to conform to the perturbed CFD surface grid.

Several tests of this aeroelastic analysis system have been successfully completed.



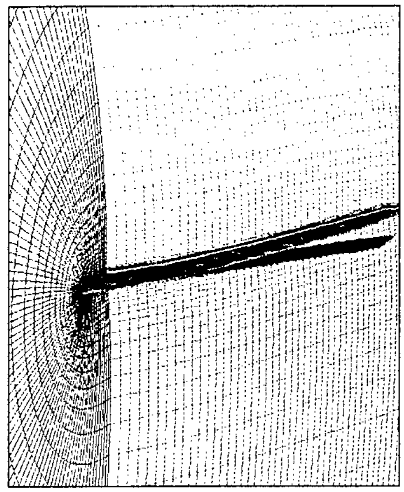
The aeroelastic analysis system is composed of five modules for the aerodynamics and structures disciplines. A typical global analysis iteration begins with a deformed (or initial) description of the geometry surface, a baseline volume CFD grid, and a complete structural model of the configuration. At the starting point of each global iteration, the surface and volume grids are passed to the grid perturbation tool, CSCMDO, to create a CFD volume grid for the new geometry. This new volume grid is passed to CFL3D for nonlinear aerodynamic analysis. To hold CPU costs down, the CFD is not fully converged (initially) at each global iteration, but is continually restarted at each iteration to converge along with the structural deformation. The level of convergence needed at each global iteration is not known *a priori*, and some trial-and-error in selecting an optimum level must be expected.

An MSC/NASTRAN finite element model (FEM) is used for the structural analysis. The aerodynamic forces are transformed from the aero surface grid to the NASTRAN structural FEM grid by the COMETRAN code. The loads (pressure as well as thermal) are applied to the NASTRAN model to obtain the structural deflections. NASTRAN has the ability to include the nonlinear changes in structural stiffness as a function of deformation. As the structure deforms under load, the geometric orientation of the FEM changes, therefore its stiffness changes. The NASTRAN structural deflections are interpolated to the aero grid using the Spline3D code. The new deflections on the aero surface grid are used by CSCMDO code to begin the next global iteration.

Grid Perturbation using CSCMDO

High Speed Aerodynamics Group — Loads and Dynamics Group

- Licensed by NASA Langley
- System is very robust and has been successfully used for complex configurations
- Output grids are of high quality with minimal CPU demands
- Portable
- Developing input deck can be labor intensive for complex configurations



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New aero grid for the structurally deformed configuration is generated by perturbing the baseline aero grid using CSCMDO. Freely licensed by NASA Langley Research Center, it produces high quality perturbed grids with low computational overhead.

CFL3D for Aerodynamic Analysis

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- Developed by NASA Langley Research Center
- Solves unsteady, compressible Euler/Navier-Stokes equations
- Finite-volume formulation
- Upwind discretization
- Choice of turbulence models
- Handles structured multiblock patched or overset grids
- Multigrid acceleration

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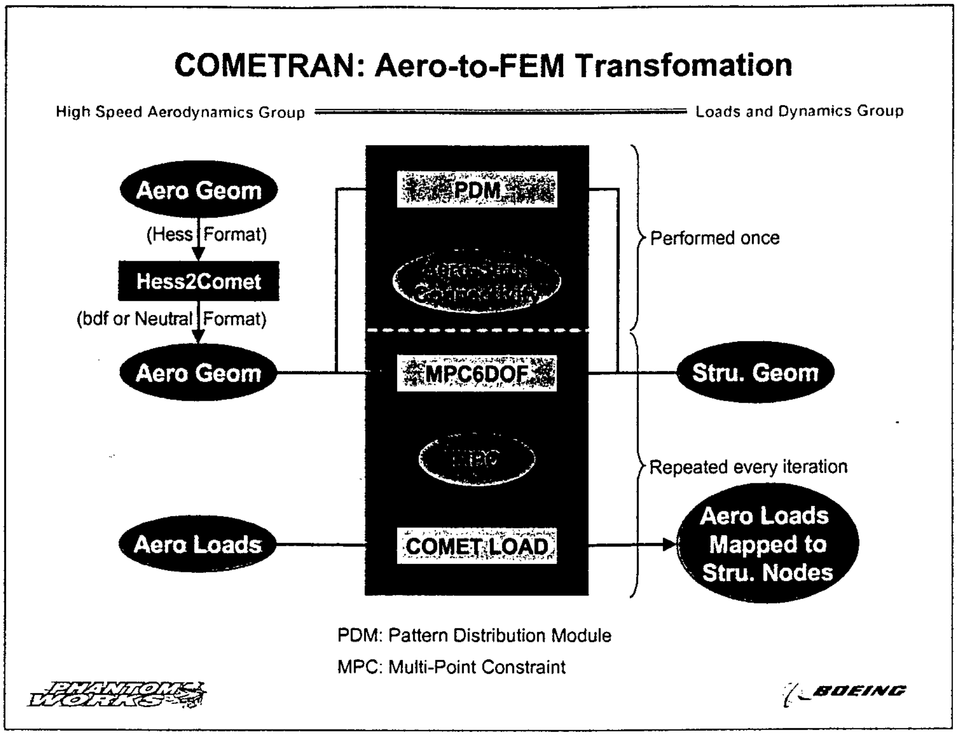
The aerodynamic analysis code is NASA's CFL3D version 6 (CFL3Dv6). It uses a finite-volume upwind formulation to discretize the Euler/Navier-Stokes equations. Both Roe's flux-difference splitting and van Leer's flux-vector splitting discretizations are available. It offers several turbulence models. The multiblock patched or overset grid handling capabilities allow for the analysis of complex configurations. Solution convergence can be accelerated using the multigrid option. It also has a built-in linear structures model for aeroelastic analysis. CFL3D has been successfully used for the aero as well as aeroelastic analysis of numerous industrial applications.

Routines to compute and output aerodynamic forces at cell-face centers of the solid surfaces and to output the coordinates of the solid-surface grid points were added to CFL3Dv6. This output is used by the grid perturbation and structures modules.



The aero loads are transferred to the structural model using COMETRAN. The inputs are the geometric definition of the aero grid and corresponding load distribution. First, COMETRAN reads the aero surface grid into the PDM (Pattern Distribution Module) code to establish the Aero-Structural Connectivity. This connectivity can be created by one of several options within PDM. Once this connectivity is established, it is not revised for subsequent load iterations. Next, this connectivity is used by the MPC6DOF (Multi-Point Constraint 6 Degree-Of-Freedom) code to generate the load transformation equations from the aero to structural grid. These equations are in NASTRAN MPC format. The COMET LOAD multiplies these equations by the applied aero loads to transform them and output them as loads on the structural model. The loads on the structural model are output in NASTRAN FORCE card format.

COMETRAN was modified to execute in batch-mode. All the input commands for COMETRAN is written to a file which it reads and executes without user intervention. Two format conversion codes, Hess2Comet and Hess2NASTRAN, were also developed to convert the aero geometry definition to a PATRAN neutral or NASTRAN bulk data format.

MSC/NASTRAN for Structural Analysis

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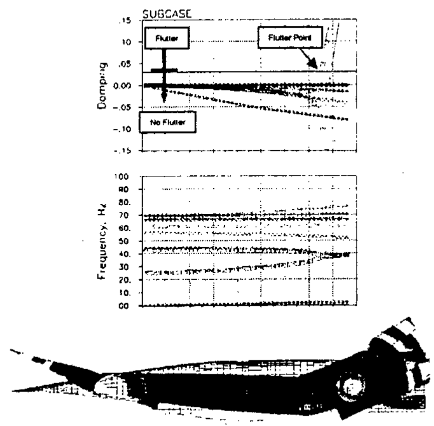
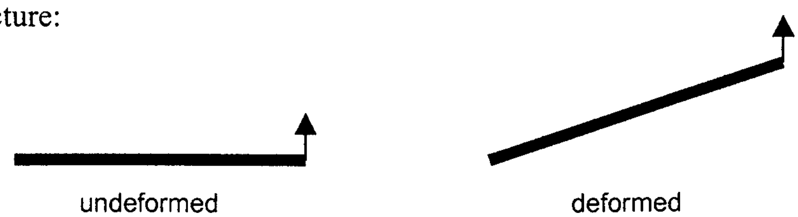
- Industry Standard Commercial Structural Analysis Code
- Static Stress Analysis
- Thermal Analysis
- Nonlinear Structural Analysis
  - Large Displacement
  - Material Nonlinear
  - Buckling
- Vibration
- Aeroelasticity

Typical NASTRAN Aeroelastic Analysis



MSC/NASTRAN is a comprehensive finite element structural analysis code. The NASTRAN analysis capabilities include static analysis with nonlinear effects: geometric, material, and temperature. Externally generated nonlinear aero loads are imported into NASTRAN and the converged nonlinear structural deflections are exported to update the shape of the aero model. The primary nonlinear structural effect included in this phase of the process is the geometric nonlinear stiffness effect. The stiffness of the NASTRAN FEM is dependent on the deformed shape of the structure. For example, consider the following structure:



The load applied to the undeformed structure is in a direction purely transverse to the orientation of the structure. Therefore, only the transverse bending stiffness acts to resist the applied load. As the structure deforms, the vertical load now acts at an angle to the structural orientation. Now, there is a component of load acting in the plane of the structure that will be resisted by the in-plane stiffness. This change in effective stiffness as a function of structural deflection and orientation is referred to as the geometric nonlinear stiffness. This system can also model certain other nonlinearities, for example, nonlinearity due to aerodynamic follower forces.

Spline3D: FEM-to-Aero Transformation

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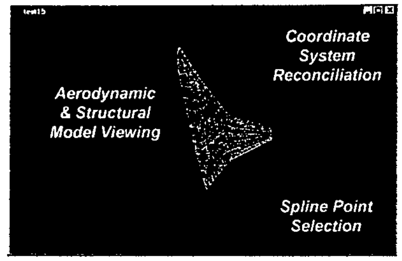
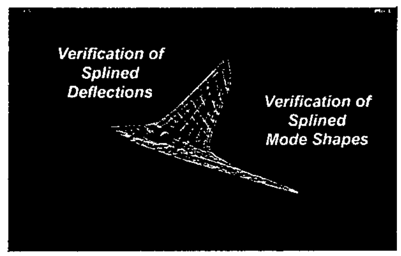
- In-House C/C++ code
- Maps structural deflections to aerodynamic grids
- Several splining options
- Generates splined deflections and spline matrix
- Interactive GUI for set-up of splines
- Can be run in batch mode for loosely-coupled aeroelastic analysis





The Spline3D code was specifically developed for the challenges of computational aeroelasticity. It contains an interactive Graphical User Interface so the user can immediately see which structural nodes are splined to which aerodynamic grid points, visualize the deflections, and get an immediate visual verification of the spline quality. In its original form, it was used only to spline vibration mode shapes from a structural (finite element) model to a computational (CFD) surface grid.

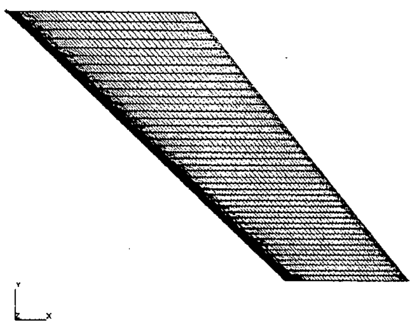
The main modification made to Spline3D for this contract was the addition of a non-interactive (batch) mode. This required modifications to the user interface portions of the code to allow file-driven operations rather than mouse-driven operations. These modifications have been completed and the code has been demonstrated in the overall aeroelastic analysis process.

Test Using AGARD 445.6 Wing

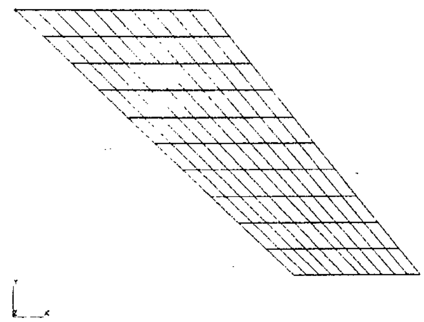
High Speed Aerodynamics Group — Loads and Dynamics Group

Tested interaction of CSCMDO, CFL3D, COMETRAN, NASTRAN, & Spline3D

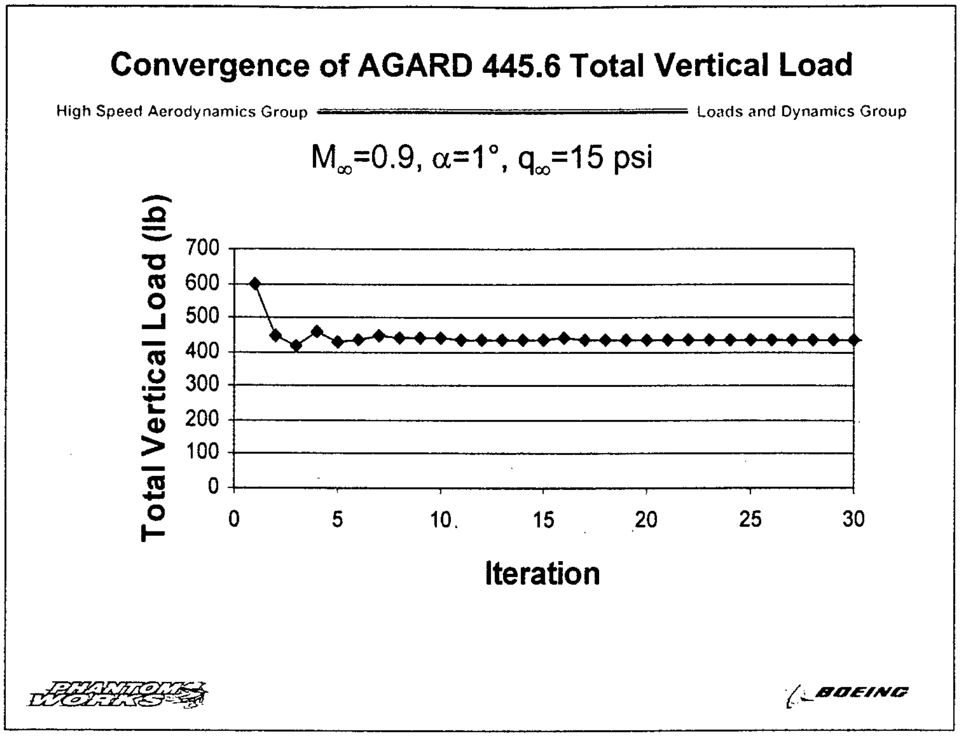
Aero Grid



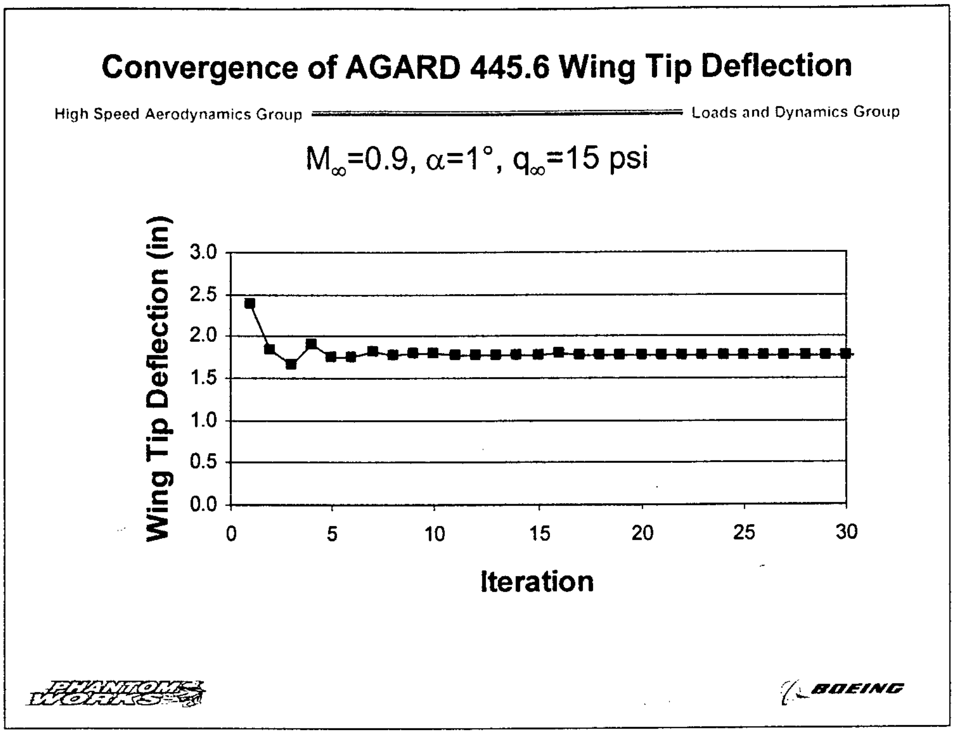
Structural FEM



In this test case, using the AGARD 445.6 wing, the entire nonlinear aeroelastic analysis process was tested. The aero grid and the structural NASTRAN FEM grid are shown. The structural NASTRAN FEM grid is coarser than the aero grid, which is usually the case for most aeroelastic models.



This chart shows the history of total vertical load at M_∞=0.9 and α=1.0°. The total vertical load converges to a constant value in less than 15 iterations. The aerodynamic analysis was performed in the Euler (inviscid) mode.



The convergence of the wing tip deflection at M_∞=0.9 and α=1.0° is shown. The wing tip deflection converges to a constant value.

Computer Resources for AGARD 445.6

High Speed Aerodynamics Group — Loads and Dynamics Group

- Memory
  - Less than 200 MB at any time
- CPU Time
  - 65% CFL3D
  - 10% COMETRAN
  - 20% NASTRAN
  - 5% Spline3D
- File I/O overhead
  - 10% of the CPU time

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Computational resource requirements will be proportional to the size and complexity of the analytic models. This simple model which has 500,000 grid points did not require a great deal of computational resources. The relative amounts of computation for the various steps of the analysis process were:

Memory: CFL3D required about 160 MB of memory while CSCMDO needed only 30 MB. The small models of COMETRAN and NASTRAN use 8 MB of memory, and the large models use 32 or 64 MB. Since sufficient memory was available, the 64MB model was used in this exercise.

CPU time: For this test problem, each global iteration required about 1 hour and 30 minutes of CPU time. Approximately 65% of the time was used by CFL3D, 10% by COMETRAN, 20% by NASTRAN and 5% by Spline3D. CPU time needed for grid perturbation using CSCMDO was negligible.

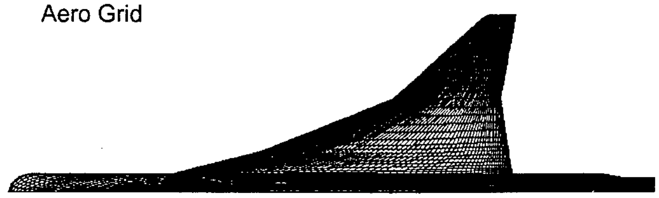
File I/O overhead: A rough estimate indicates that file I/O consumes less than 10% of the total time.

Test using HSR Flexible Semispan Model (FSM)

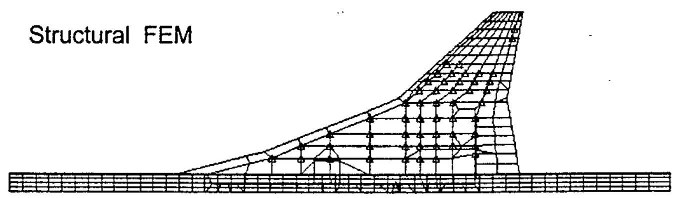
High Speed Aerodynamics Group — Loads and Dynamics Group

Tested interaction of CSCMDO, CFL3D, COMETRAN, NASTRAN, & Spline3D

Aero Grid



Structural FEM



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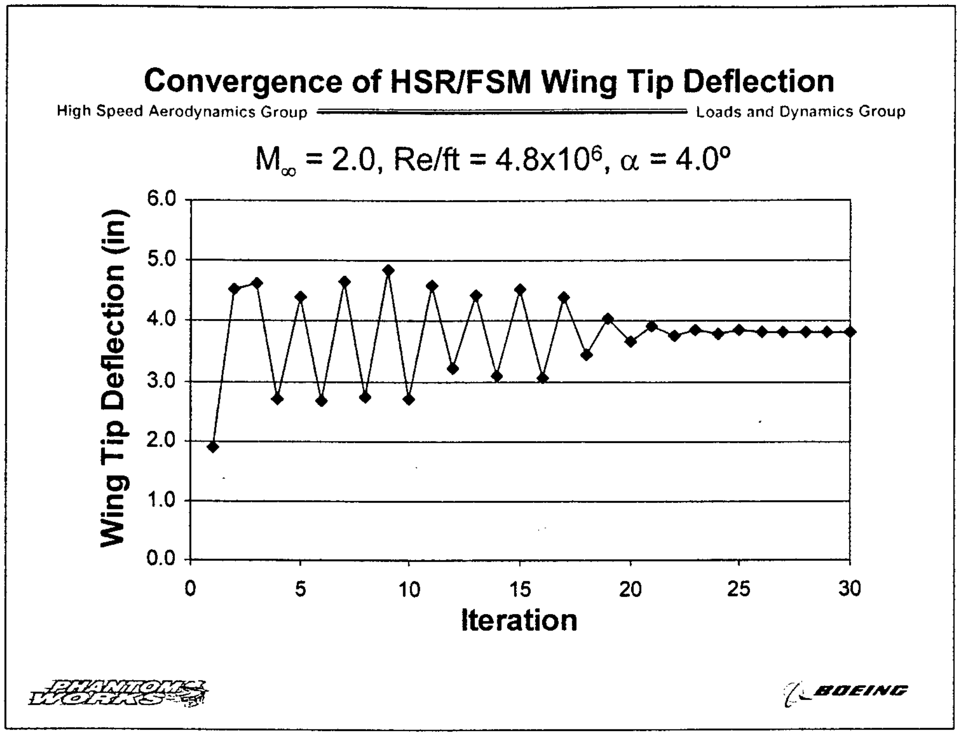
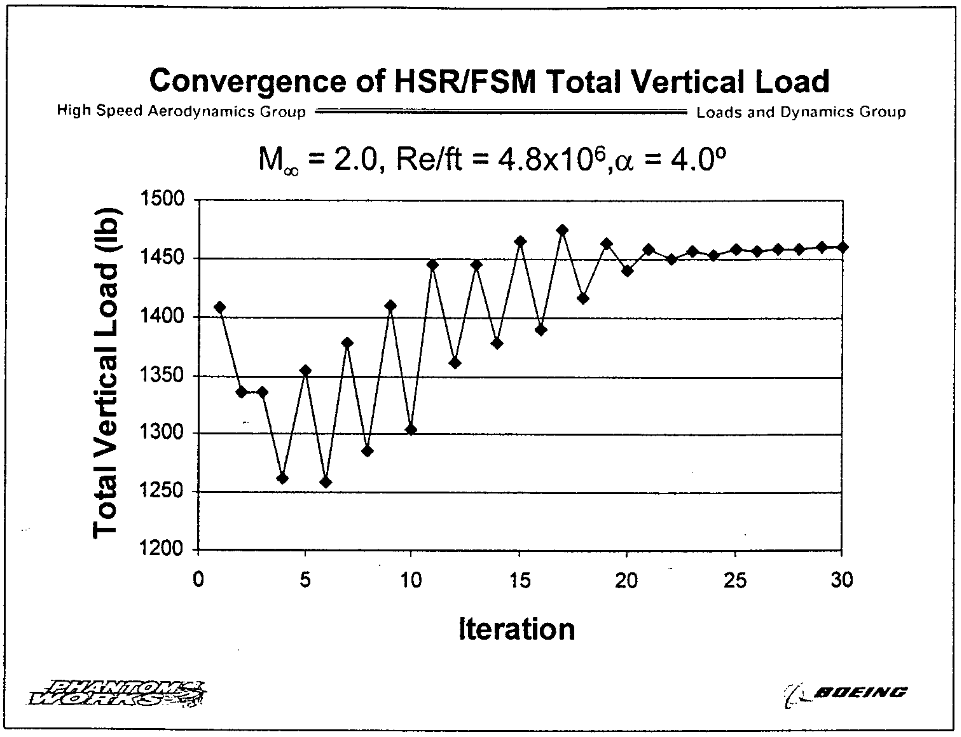
In this case, the nonlinear aeroelasticity analysis system was tested using the High Speed Research (HSR) Flexible Semispan Model (FSM) wing/body model. The aero grid and the structural NASTRAN FEM grid are shown. This model was created as part of the Aeroelaticiy Wind Tunnel Models program during the NASA/Industry HSR program. The structural NASTRAN FEM grid is coarser than the aero grid, which is usually the case for most aeroelastic models. Here, the aerodynamic analysis was performed in the Navier-Stokes (viscous) mode.



The convergence of the HSR/FSM wing tip deflection, for the case with M_∞=2.0 and α=4.0° is shown here. After 15 iterations it was noted that the CFD sub-iteration was not reducing the residual sufficiently. This led to non-convergence of the global problem. After the 15th iteration, convergence parameters within the CFL3D were modified, leading to convergence toward a constant deflection. A "smarter" convergence monitoring routine in CFL3D could possibly reduce the number of global iterations required to obtain an aeroelastic solution.



This chart shows the history of total applied vertical load on the HSR/FSM for the case with M_∞=2.0 and α=4.0°. Once again, after modifying the convergence parameters within CFL3D after the 15th iteration, total vertical load converged to a constant value.

HSR/FSM Wing Deflection

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$M_\infty = 2.0$, $Re/ft = 4.8 \times 10^6$, $\alpha = 4.0°$

(Deflections are not exaggerated)

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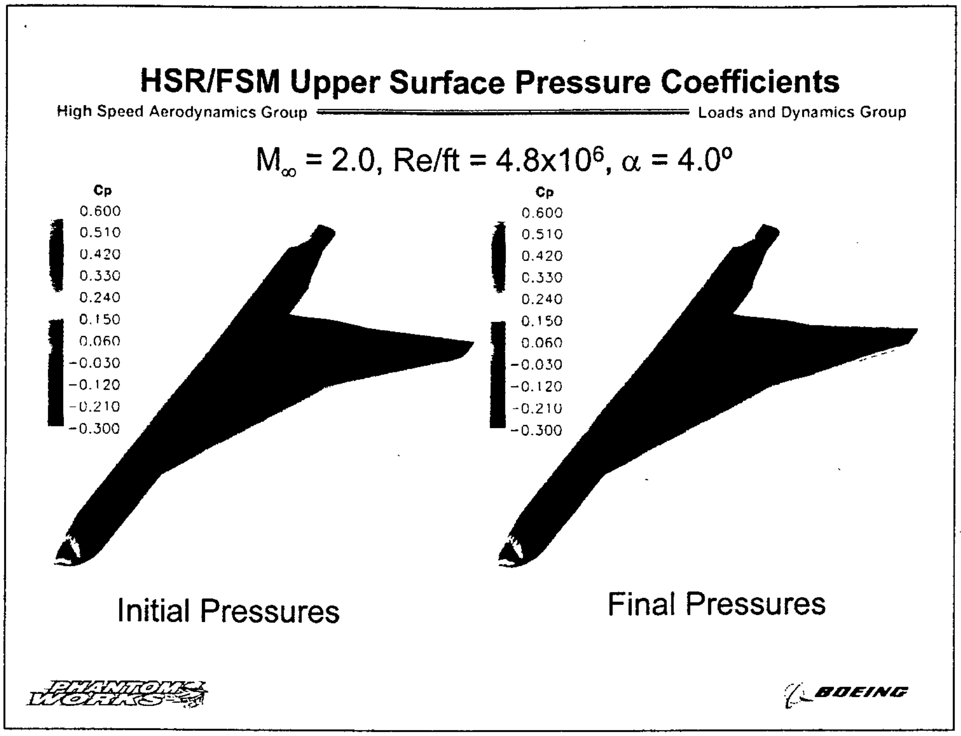
Wing deflections for the initial and final iterations are shown. This problem setup did not induce overly large deflections. However, note that the wing does not merely deform in shear as in many linear applications. This distinction will become more apparent in applications with more significant deformations.

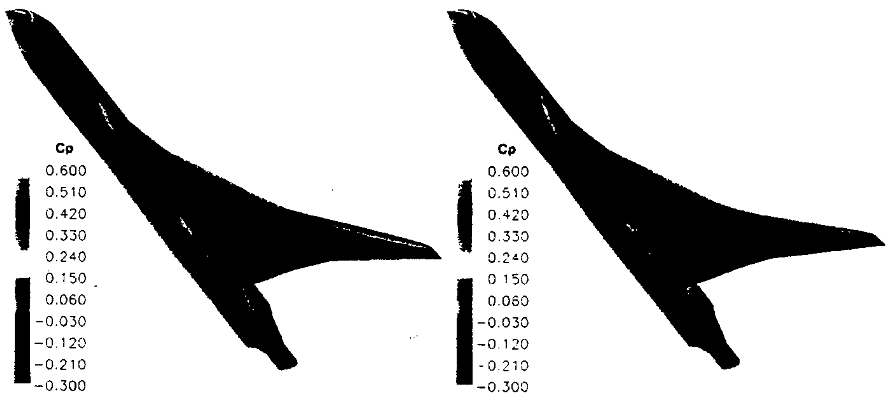


Upper surface pressure coefficients on the initial undeformed and final deformed FSM model test case are shown. Loads were kept fairly low during this test case, so while the deflections and changes in pressure can be seen, they are not very large. However, the deformed wing does have less vertical loading on the outboard panel as expected due to the washing-in of the wing twist (note the increased pressures on the outer panel in the deformed geometry).

HSR/FSM Lower Surface Pressure Coefficients

High Speed Aerodynamics Group — Loads and Dynamics Group

$M_\infty = 2.0$, $Re/ft = 4.8x10^6$, $\alpha = 4.0°$



Initial Pressures Final Pressures

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Lower surface pressure coefficients on the initial undeformed and final deformed FSM model test case are shown. The deformed wing does have less vertical loading on the outboard panel as expected due to the washing-in of the wing twist (note the lower pressures on the outer panel in the deformed geometry).

Computer Resources for HSR/FSM

High Speed Aerodynamics Group — Loads and Dynamics Group

- Memory
  - Less than 400 MB at any time
- CPU Time
  - 93% CFL3D
  - 2% COMETRAN
  - 4% NASTRAN
  - 1% Spline3D
- File I/O overhead
  - 2% of the CPU time

This model, which has about 1×10^6 grid points, required significantly more resources than the first test problem. The relative amounts of computation for the various steps of the analysis process were:

Memory: CFL3D required about 320 MB of memory while CSCMDO needed only 30 MB. The small models of COMETRAN and NASTRAN use 8 MB of memory, and the large models use 32 or 64 MB. Since sufficient memory was available, the 64MB model was used in this exercise.

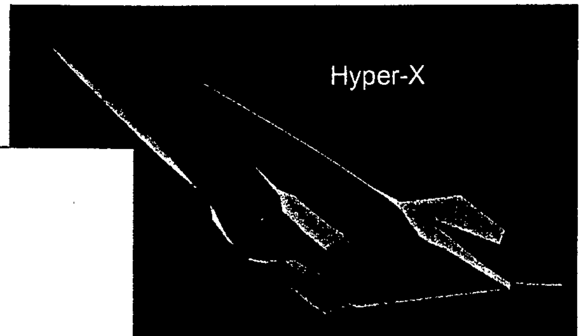
CPU time: For this test problem, each global iteration required about 7 hours of CPU time. Approximately 93% of the time was used by CFL3D, 2% by COMETRAN, 4% by NASTRAN and 1% by Spline3D. CPU time needed for grid perturbation using CSCMDO was negligible.

File I/O overhead: A rough estimate indicates that file I/O consumed less than 2% of the total time.

The significant increase in CPU time for the CFD analysis was due to the use of Navier-Stokes analysis and the increase in number of iterations that were necessary for the CFD iterations to converge.

Hyper-X Follow-On Vehicle

High Speed Aerodynamics Group — Loads and Dynamics Group



- Similar to Hyper-X
- To be built by 2002
- Mach 7 vehicle
- OML is ready
- Structural layout is available
- Structurally flexible
- Hot and cold structures

The first real application of this system will be to analyze the aeroelastic characteristics of the Hyper-X follow-on vehicle. This vehicle, expected to be built by 2002 and flown soon after that, is designed to fly at Mach 7 for about 20 minutes. Unlike the current Hyper-X, the follow-on vehicle is longer and significantly more flexible. The control surfaces do not have any thermal protection system (TPS) and could get extremely hot.

Work In Progress

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- Creating CFD grid for the Hyper-X follow-on vehicle
- Creating FEM for the Hyper-X follow-on vehicle
- Adding equilibrium gas model to CFL3D

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The primary goal for next year is to use this system to perform aerothermoelastic analysis of the Hyper-X follow-on vehicle. The OML for the vehicle has been obtained and the CFD grid generation is in progress. The structural FEM is being created as part of another task.

Additionally, in order to model the correct flow physics at Mach 7, an equilibrium gas model is being added to CFL3D.

CFL3DEv6: Extension of CFL3D Euler/Navier-Stokes Solver to Equilibrium Gas Flows

High Speed Aerodynamics Group — Loads and Dynamics Group

- Objective
  - Extend nonlinear aeroelasticity analysis capability for hypersonic air vehicles by adding an equilibrium gas modeling capability
- Approach
  - Modify Euler/Navier-Stokes solver CFL3D to minimize impact on current nonlinear aeroelastic analysis framework
  - Implement equilibrium gas model
    - » valid for 5<M<10
    - » compatible with CFD methodology in CFL3D
- Accomplishments
  - coding complete
  - testing imminent
- Plans
  - Validate added capability with experimental data

	Eq. of State	γ
perfect gas	$p=\rho RT$	$\gamma = \frac{c_p}{c_v}$
equilibrium gas	$p=\rho ZRT$	$\gamma = 1 + \frac{p(e,\rho)}{\rho e}$

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The current version of CFL3D (v6) can model the dynamics of only perfect gases. In order to capture the correct physics at Mach 7, which is the design speed of Hyper-X follow-on vehicle, an equilibrium gas model is being added to CFL3D.

The coding is complete and testing and validation with experimental data will be completed soon.